AD-A142 820 AIRBLAST SIMULATIONS USING FLUX-CORRECTED TRANSPORT CODES(U) NAVAL RESEARCH LAB WASHINGTON DC D L BOOK ET AL. 30 MAY 84 NRL-MR-5334 SBI-AD-E000 576 1/1

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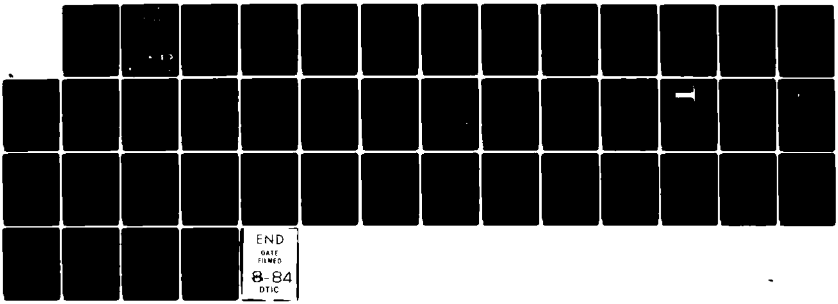

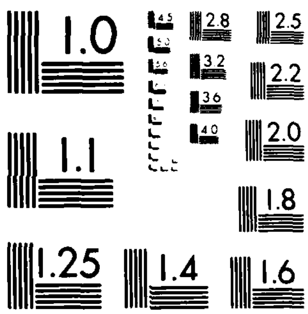

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): NRL Memorandum Report 5334	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION: Naval Research Laboratory; 6b OFFICE SYMBOL (If applicable): Code 4040	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State and ZIP Code): Washington, DC 20375	7b ADDRESS (City, State and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION: Defense Nuclear Agency; 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State and ZIP Code): Washington, DC 20305	10 SOURCE OF FUNDING NOS.: PROGRAM ELEMENT NO: ; PROJECT NO: ; TASK NO: ; WORK UNIT NO: DNO-91230
11 TITLE (Include Security Classification): (See page ii)	
12 PERSONAL AUTHOR(S): D.L. Book and M.A. Fry*	
13a TYPE OF REPORT: Interim; 13b TIME COVERED: FROM TO	14 DATE OF REPORT (Yr., Mo., Day): May 30, 1984; 15 PAGE COUNT: 45
16 SUPPLEMENTARY NOTATION: *Science Applications, Inc., McLean, VA 22102 (Continues)	
17 COSATI CODES: FIELD / GROUP / SUB GR.	18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Flow fields resulting from the passage of a blast wave through a mixture of high-explosive detonation products and air can be significantly altered as compared to a single-phase medium. The description of the two-phase flow has been numerically simulated in one (1-D) and two-dimensional (2-D) calculations using multi-dimensional flux-corrected transport (FCT) techniques. Calculated and experimentally determined flow field have been compared.

FCT is a finite difference technique for solving fluid equations in problems where sharp discontinuities arise. Shocks, slip surfaces, and contact surfaces are accurately modeled through the application of diffusion and antidiffusion at each timestep. This diffusion is just large enough to prevent dispersive ripples and guarantees that all physically positive conserved quantities remain positive. Simulation of two-phase flow is a natural outgrowth of the FCT technique. Each species is treated as a separate fluid with the pressure terms in the energy and momentum equations providing the coupling. Moreover, the

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20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED X SAME AS RPT ☐ DTIC USERS ☐	21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL: David L. Book	22b TELEPHONE NUMBER (Include Area Code): (202) 767-2078; 22c OFFICE SYMBOL: Code 4040

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE

11. TITLE (Include Security Classification)

Airblast Simulations Using Flux-Corrected Transport Codes

16. SUPPLEMENTARY NOTATION (Continued)

This work was supported by the Defense Nuclear Agency under Subtask N99QAXAH, work unit 00061, work unit title "Cloud Calculations," and under Subtask Y99QAXSG, work unit 00057, work unit title "Airblast Calculation."

19. ABSTRACT (Continued)

timestep-split feature of the most recent version of FCT allows extension from 1-D to 2-D simulation. Results are compared with shock tube and field test data.

CONTENTS

AIRBLAST SIMULATIONS USING FLUX-CORRECTED TRANSPORT CODES

INTRODUCTION

The method of Flux-Corrected Transport (FCT) was developed about ten years ago (Boris and Book, 1973; Book, et al, 1975; Boris and Book, 1976) as a means for solving systems of hyperbolic equations in such a way that physically positive quantities remain positive. Its principal application has been to compressible fluids, i.e., fluids in which some of the flow speeds are comparable with or greater than the local speed of propagation of waves in the medium. Examples include plasmas, combusting systems, and gas-dynamic flows.

Subsequently the method has been extended and generalized in a number of important respects. These include the construction of general-purpose algorithms for solving fluid equations on moving nonuniform grids in a curvilinear coordinate system (Boris 1976), strictly multidimensional FCT algorithms (Zalesak 1979) (as opposed to timestep-splitting of one-dimensional algorithms), and variants on these. In addition, numerous techniques have been developed by other workers which incorporate the positivity-preserving property in other ways (Harten, 1978; Van Leer 1979; Collela, 1983). The weight of opinion among computational scientists who deal with problems of compressible flow now strongly affirms the superiority of positivity-preserving methods over conventional ones. In a few words, advantages are improved robustness, flexibility, resolution, and freedom from nonphysical numerical artifacts.

Manuscript approved February 2, 1984.

In this paper we describe some applications of FCT to airblast problems, i.e., to calculations of the blast wave and fireball produced by an explosion in the atmosphere near the ground. As this is one of the applications for which FCT was originally devised, it is not surprising that the method yields satisfactory results in a wide range of cases with very little need for computational development. Nevertheless, some of the refinements we have employed in this connection are of interest both in their own right and for other users who may need to carry out similar calculations.

In most of the airblast calculations we have carried out, four distinct stages are discernible: (i) initialization, usually employing a Chapman-Jouguet model (Kuhl et al, 1981) to describe conditions at the time the detonation wave reaches the periphery of the explosive charge; (ii) free-field (one-dimensional) evolution, before the shock reaches the ground; (iii) subsequent two-dimensional evolution using axisymmetric (r-z) geometry; and (iv) postprocessing of the resulting solution to analyze and display the results.

The advances described in this paper relate to all but the first of these states. They may be cataloged as follows: refinements in the free-field solution; development of a regridding algorithm for the early-time (high-overpressure) two-dimensional solution; improvements in boundary conditions in the two-dimensional stage; and exploitation of tracer particles as a diagnostic, particularly in the late stages of fireball evolution, after shock breakaway. In the body of the paper one section is devoted to each of these topics.

REFINEMENTS IN THE FREE-FIELD SOLUTION

Figure 1 shows one-dimensional (spherical) profiles calculated using a form of the general-purpose FCT algorithm ETBFCT (Boris (1976). Although these profiles are accurate and physically correct on the average, they exhibit numerous flat shelves and accompanying sharp drops, especially in the region of the rarefaction wave. This phenomenon is known as "terracing." In this instance we attribute its presence to the nonlinear action of the flux limiter stage of FCT on dispersive errors from the transport stage.

To explain what this means, let us describe a class of FCT algorithms which includes ETBFCT as a particular case. To advance the one-dimensional continuity equation

$$\frac{\partial \rho}{\partial t} = - \frac{\partial}{\partial x} (\rho v) \tag{1}$$

one time step on a uniform mesh with a given flow velocity v, we suppose the old cell-centered values ρ_j^o and v_j are known. A general three-point conservative finite-difference operator acting an ρ_j^o can be written in the form

$$\begin{aligned} \rho_j^T = \rho_j^o - \epsilon_{j+1/2}\, \rho_{j+1/2} + \epsilon_{j-1/2}\, \rho_{j-1/2} \\ + \gamma_{j+1/2} (\rho_{j+1}^o - \rho_j^o) - \gamma_{j-1/2} (\rho_j^o - \rho_{j-1}^o), \end{aligned} \tag{2}$$

where $\rho_{j+1/2} = \frac{1}{2}\, \rho_j + \rho_{j+1})$. To obtain a first-order approximation to Eq. (1), we must define $\epsilon_{j+1/2}$ to be the Courant number $v_{j+1/2}\delta t/\delta x$, where $v_{j+1/2} = \frac{1}{2} (v_j + v_{j+1})$; likewise, for a conventional scheme with second-order (spatial) accuracy, we must let $\gamma_{j+1/2} = \frac{1}{2}\, \epsilon_{j+1/2}^2$. In FCT, however, a numerical diffusion is applied to ρ_j^T according to

$$\rho_j^{TD} = \rho_j^T + \nu_{j+1/2}(\rho_{j+1}^o - \rho_j^o) - \nu_{j-1/2}(\rho_j^o - \rho_{j-1}^o) \; . \qquad (3)$$

Evidently the γ's and the ν's combine in the same way in ρ_j^{TD}, so we leave both unspecified for the moment.

If we now applied another diffusion operation, this time with the opposite sign, it would just tend to cancel the diffusion terms already present in ρ_j^{TD}. Instead we write for the new densities ρ_j^n

$$\rho_j^n = \rho_j^{TD} - \phi_{j+1/2}^c + \phi_{j-1/2}^c , \qquad (4)$$

where the "corrected" fluxes $\phi_{j+1/2}^c$ differ from the "raw" fluxes $\phi_{j+1/2} = \mu_{j+1/2}\,(\rho_{j+1}^o - \rho_j^o)$ in two ways: we use $\{\rho_j^T\}$ instead of $\{\rho_j^o\}$ in the definition of the raw fluxes (this allows us to define γ so as to optimize some property in the difference scheme, as will be seen shortly); and we correct the fluxes, so that the antidiffusion process (which evidently tends to make all gradients steeper) can enhance no extrema already present in $\{\rho_j^{TD}\}$, nor introduce any new ones. The simplest formula for achieving this in all possible situations is that used in "strong flux limiting:"

$$\phi_{j+1/2}^c = S\cdot\{\max[0, \min(|\phi_{j+1/2}|, \Delta_{j-1/2}, \Delta_{j+3/2})]\} , \qquad (5)$$

where $S = \text{sign}\ \phi_{j+1/2}$ and $\Delta_{j+1/2} = \rho_{j+1}^{TD} - \rho_j^{TD}$.

At most points in a gently varying profile no correction is required and $\phi_{j+1/2}^c = \phi_{j+1/2}$. In that case we can perform a Von Neumann analysis, calculating the complex propagator or amplification factor $A = A_r + iA_i = \rho_j^n/\rho_j^o$ for a sinusoidal density profile $\rho_j^o = \exp(ijk\ \delta x)$, where k is the wave number. Writing $\beta = k\delta x$ and $\varepsilon = v\delta t/\delta x$, we expand in powers of β the amplification

$$|A| = 1 + A_2\ \beta^2 + A_4\ \beta^4 + \ldots \tag{6}$$

and the relative phase error

$$R = \frac{1}{\beta\varepsilon} \tan^{-1} (A_i/A_r) - 1 = R_2\ \beta^2 + R_4\ \beta^4 + \ldots \tag{7}$$

It is easy to show that the condition that A_2 vanish is

$$\gamma + \nu - \mu = \frac{1}{2}\ \varepsilon^2 . \tag{8}$$

The condition that R_2 vanish is

$$\mu = \frac{1}{6} - \frac{1}{6}\ \varepsilon^2 . \tag{9}$$

There remains one free parameter which can be chosen so as to build some desirable property into the algorithm (this is the reason for introducing γ). The choice $\gamma = \frac{1}{2}\ \varepsilon^2$ confers no particular benefit. Letting $\gamma = 0$ as in ETBFCT (Boris, 1976) reduces the operation count and yields a useful general-purpose algorithm, which is, however, subject to the terracing problems mentioned previously. There are two other obvious candidates: $\gamma = \frac{1}{4}\ \varepsilon^2$, which implies $A_4 = 0$, and $\gamma = \frac{1}{5} + \frac{1}{5}\ \varepsilon^2$, which implies $R_4 = 0$.

Figure 2 shows this for a test involving passive advection with a uniform velocity. A test profile, initially consisting (Fig. 2a) of a half ellipse, connected by two quarter ellipses to a straight line of zero slope, is advected with a Courant number $\varepsilon = 0.2$. The results obtained using the general-purpose algorithm (Fig. 2b) and the new multicoefficient version (Fig. 2c) are shown for comparison. It is clear that the latter represents a distinct improvement, a conclusion that continues to hold for other test profiles.

The results of a different test are shown in Fig. 3. In Fig. 3a, the profile obtained from an analytic solution of the bursting diaphragm (Riemann) problem with 10-to-1 density ratio and 10^3-to-1 pressure are plotted, while in Fig. 3b those calculated with the new FCT algorithm are shown for comparison. Here again the results agree fairly closely. The agreement is worst near the contact surface, which, unlike the shock, has no physical self-steepening mechanism.

In chemical explosions a characteristic feature is the contact surface between the detonation products and the air compressed ahead of the blast (Fig. 4). In the absence of diffusion (usually a good approximation in an actual explosion, if not numerically), the contact surface remains sharp, and the two media differ in density across this discontinuity by ~ 30%.

In an airblast, a layer of air is compressed beneath the burst, so that the detonation products never reach the ground. The shock wave propagates down to the ground, reflects upward, and propagates back through the layer of compressed air. When it encounters the contact surface, it is partly transmitted and partly reflected downward again. This process can repeat several times. At finite ground range the shocks reflect obliquely and soon propagate away from the fireball, but directly beneath the burst the process is only terminated when the rising fireball recedes from the ground sufficiently far. (Experimentally and computationally the multiply reflected shocks usually become indistinguishable from noise after the second or third reflection.)

Therefore it is important computationally to model the contact surface accurately if these shock reverberations are to be described properly. If the contact surface in the simulation is diffuse, the shock reflected from it will be weak or undetectible. (If physical diffusion processes were present experimentally but absent in the simulation, however, the latter would predict excessively strong reflection.) The results shown in Fig. 4a, calculated using 200 zones, while close to the physically correct profiles, exhibit considerable diffusion at the contract surface. This is in contrast with the results shown in Fig. 4b, obtained using 400 zones, in which the contact surface is much more distinct. A consequence of improving the resolution is shown in Fig. 5, which depicts the pressure history that a sensor beneath the bursts shown in Fig. 4 would measure. The peaks are due to the initial shock and the shock re-reflected from the contact surface, respectively. Note that both maxima increase when the resolution improves, but the second peak rises more. Although in this case further enhancement of the diffusion makes little difference, it is clear that the second peak might in some cases be raised above the first. Thus a qualitative change in the solution can result from improving the resolution. This is of course also applied to the accuracy of the two-dimensional results calculated after the one-dimensional solution is laid down on 2D mesh.

REGRIDDING ALGORITHM FOR TWO-DIMENSIONAL SOLUTION

To study the transition to Mach reflection extremely high resolution is required, as may be seen from the following discussion. The Mach stem at transition has vanishing length. If we are restricted to resolution of features several (say, a factor of three) times the mesh size $\delta x \sim \delta y$, then the ground range at which transition occurs will be overestimated by an amount $\delta \ell$ equal to this length divided by the tangent of the opening angle χ, which is typically a small fraction of a radian, so the $\delta \ell \sim 30\ \delta x$. Since core limitations restrict us to meshes with a total of no more that 10^4 - 10^5 zones and since transition typically takes place at a ground range comparable with the height of burst (HOB), if we use a uniform mesh the error $\delta \ell$ would be as much as ten or twenty percent of the HOB.

Fortunately, this is unncessary. We can grid up near where transition takes place, using cells smaller by one or two orders of magnitude in each direction, with a proportionate reduction in $\delta \ell$. Since the mesh is rectilinear, this implies the presence of extremely elongated (non-square) zones on portions of the grid, with consequent errors in the solution. This creates no difficulties if the details of the flow there are unimportant and if those regions do not generate errors which propagate into the regions of chief interest.

However, a shock wave propagating from coarsely gridded region abruptly into a finely gridded one sheds sound waves as it steepens up, seriously degrading the solution at and behind the front (Boris and Book (1976)). Hence it is necessary to ensure that the shock at the front of the blast wave be allowed to propagate some distance through a finely gridded region prior to reaching the point of reflection, that the transition be gradual, and most significantly, that this be true not just at transition but at all times up until then. The only way to avoid using an inordinate number of fine zones is to move the highly resolved region with the reflection point, starting at the instant the blast wave reaches the ground and continuing as long as the Mach reflection process is the interest (Fig. 6). This method exploits the "sliding rezone" (continuous regridding) capability of the ETBFCT algorithm.

Typically we start with a mesh ~ 150 x 150 zones, having ~ 100 fine zones of dimension $\delta x = \delta y$ and ~ 50 coarse zones of dimension $\Delta x = \Delta y$ in each coordinate direction, with $\Delta x / \delta x = 10$. The fine zones are those closest to the axes. Let the cell boundaries be specified by $\{x_i\}$ and $\{y_j\}$. We introduce a smooth transition region by diffusing these interfaces repeatedly according to

$$x_i' = x_i + \eta(x_{i+1} - 2x_i + x_{i-1}) \tag{10}$$

$$y_j' = y_j + \eta(y_{j+1} - 2y_j + y_{j-1}), \tag{11}$$

where the diffusion coefficient η is of order 0.1. The diffusion process is repeated N times (N ~ 30) to generate a transition region N cells wide. The initial reflection necessarily occurs in the fine-zoned region.

As the reflection point moves outward, the grid is redefined each cycle. We search on density (or pressure) to find the smallest radial displacement such that conditions deviate from ambient by a significant amount (3%).

Using this as a center, we define new cell boundaries, smooth $\{x_j\}$ and $\{y_j\}$ as before, and deposit the transported fluid quantities into the cells of this new grid at the conclusion of the transport calculation. As the fine-zoned region marches outward, coarse cells disappear ahead of it and reappear at small radii (Fig. 6).

This method has proved successful on a number of HOB calculations. A certain amount of tuning is necessary to ensure that enough zones are present in both the highly resolved and transition regions, but there is no difficulty in tracking the reflection point, nor is any significant detail lost through diffusion.

BOUNDARY CONDITIONS

The conditions for reflection at a planar solid boundary in a perfectly invisid flow are

$$\frac{\partial \rho}{\partial n} = \frac{\partial p}{\partial n} = \frac{\partial v_t}{\partial n} = v_n = 0, \tag{12}$$

where $\frac{\partial}{\partial n}$ represents a normal derivative and the subscripts n and t label the normal and tangential components of velocity. These conditions are imposed at the interface between the last cell of the computational mesh and a guard cell juxtaposed to it. To ensure that the normal derivative of a quantity f vanish, it is sufficient to set the value in the guard cell equal to that in the last internal cell, i.e., $f_{N+1} = f_N$. To ensure that the quantity itself vanish, we simply set $f_{N+1} = -f_N$. (Special attention must be paid to the equation describing the component of momentum normal to the boundary in order that no momentum be diffused through the interface.) Equation (12) applies to any symmetry plane or axis, and so to the axis of symmetry in the HOB problem at $r=0$. At large values of r and z (i.e., at the peripheral boundary -- the outside and top of the mesh), we impose the ambient conditions $\rho = \rho_a$, $p = P_a$, $v = 0$.

This is satisfactory until shocks propagate to the boundary. If we are interested in following the shocks further, it is necessary at this point to begin moving the grid outward (as described in the previous section), or to lay down the solution on a larger, coarser mesh. If we are interested in characteristic late-time phenomena such as vortex formation and fireball rise, however, shocks are irrelevant and it is appropriate to use simple outflow (or transmission) boundary conditions, namely

$$\frac{\partial \rho}{\partial n} = \frac{\partial p}{\partial n} = \frac{\partial v}{\partial n} = 0 \qquad (13)$$

Higher-order extrapolation schemes have been recommended in the literature (see e.g., Roache 1972), but have not been found particularly useful in connection with FCT, apparently because of the way they interact with FCT's tendency to clip off the tops of peaked profiles. At very late times a small but significant modification, suggested by Boris (personal communication, 1983) has been employed. This involves introducing a relaxation term at the peripheral boundary in the form

$$f_{N+1} = f_N + \alpha(f_a - f_N) \qquad (14)$$

Here the relaxation coefficient satisfies $\alpha = c_a \delta t/L$, where c_a is the ambient speed of sound and L is a typical scale size (e.g., fireball cloud diameter) in the problem. Typically α is small, $\alpha \sim 10^{-2} - 10^{-3}$. Its effect is to cause the peripheral values of the fluid variables to relax toward their ambient values, simulating the influence of inflow from the surrounding atmosphere.

Also at very late times (typically tens of seconds), gravity must be included in the vertical momentum equation to describe the effect of buoyancy. The equation we solve has the form

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial}{r\,\partial r}(r\,\rho u v) + \frac{\partial}{\partial z}(\rho v^2) + \frac{\partial}{\partial z}(p - p_a) \tag{15}$$

$$+ (\rho - \rho_a)g = 0.$$

The ambient quantities, which are taken from tables, are the same as those used in the initial conditions. These represent a hydrostatic balance which truncation errors will not destabilize.

The energy equation also acquires an additional term due to gravity; this, however, plays only a minor role.

Figure 7 shows the late time evolution of a fireball calculated for a 600-ton burst of high explosive (HE) set off at a height of 50.6 m. Note the elongation of the cloud and the characteristic vortices which appear especially clearly in the HE density contours.

GRAPHICS DEVELOPMENTS

Approximately one quarter of our computational costs are accumulated in generating pictures showing the results of the calculation. These take the form of pressure histories; plots of the surface pressure and density vs range; velocity vector (arrow) plots; contours of constant total and HE product mass density, total and internal energy density, pressure, and vorticity; instantaneous locations or trajectories of passively advected tracer particles; and movies of the time variation of these displays. Both the latter and the use of distinguishing colors are particularly revealing, although examples can not be presented here. In three-dimensional work we have carried out (Fry and Book 1983, unpublished), the problems of displaying results become significantly greater.

The approach we have taken is to perform the calculation in its entirety first, often with several restarts, producing only enough pictures to make sure everything is going well, and dumping out the results (essentially the two-dimensional ρ, u, v, and p arrays) at intervals onto magnetic tape. This means that if we require a posteriori a quantity which cannot be deduced from the data in the dump files (such as the total impulse on the ground sensors or the pressure history at a location where no sensor existed), the calculation has to be rerun. This is true also if the dump interval chosen is too long, but in many cases intermediate values can be obtained satisfactorily by interpolation. For example, a movie of some 700 frames was made using linear interpolation between twenty-seven dumps. (Cubic interpolation would have required generating a new data type containing only the arrays being processed, since the contents of four dumps cannot be fitted into core simultaneously.) The graphics calculations, like the hydrodynamics calculation themselves, were performed on a Texas Instruments ASC, a two-pipe vector machine with approximately half a million words of core. The plots were output on a Tektronix 4014 scope; the color movie was generated using a dicomed graphics system. This approach, in which we generated graphics by postprocessing a limited number of dump files, is a compromise between generating all the graphics in the course of the calculation and saving the results from every timestep. (This would entail prohibitive disk or I/O requirements.) In general it has worked well particularly as we have learned from experience what quantities should be saved and how often they should be dumped.

In concluding, we remark that passive advection of tracer particles is among the most useful of the graphical display we have used, particularly in movies. Figure 8 shows tracer particle histories over two time intervals for the calculation described previously. Note that four distinct vortices are revealed in these pictures, two in the "forward" direction and two reversed. In previous work (both experimental and in simulations), only one of each had been detected. Moreover, we are not restricted to passive advection, which is appropriate to the motion of infinitesimal particles in the blast wind fields. We have also modeled finite-sized particles (dust and debris) by balancing inertial forces against gravity and the Stokes drag according to

$$m\frac{dV}{dt} = -mg + D(v - V), \tag{16}$$

where m and V are the particle mass and velocity, respectively, and D is the drag coefficient. By using (16) with a spectrum of particle masses $\{m_i\}$ and appropriate initial conditions obtained from an ejecta model, we can generate realistic maps showing how must material is entrained by the blast and where it is located at any given time. This is invaluable for comparison with observations of field tests, where the obscuring debris clouds are among the most conspicuous features.

ACKNOWLEDGMENT

This work was supported by the U.S. Defense Nuclear Agency under Subtask N99QAXAH, Work Unit #00061, Work Unit "Cloud Calculations," and under Subtask Y99QAXSG, Work Unit #00057, Work Unit Title "Airblast Calculation."

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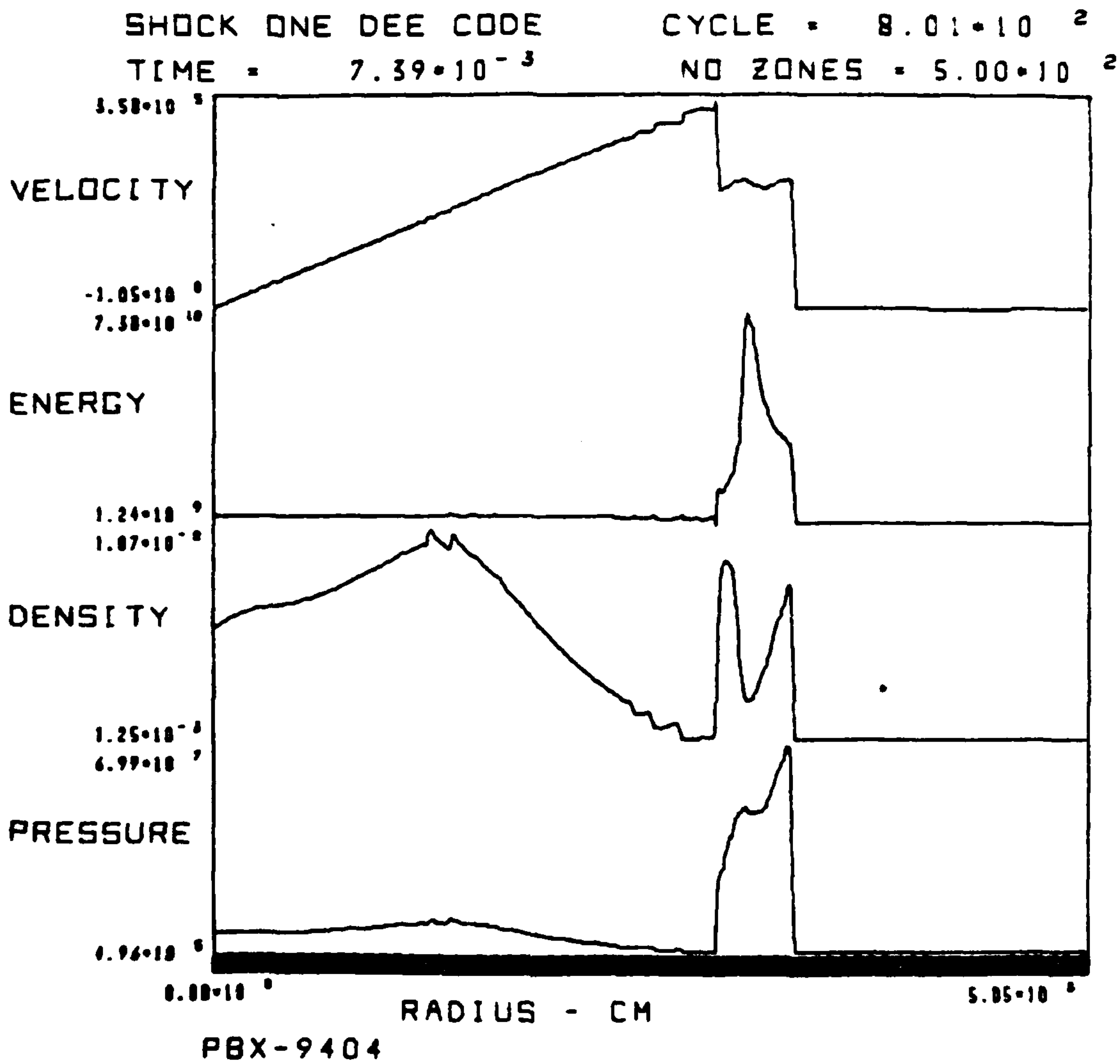

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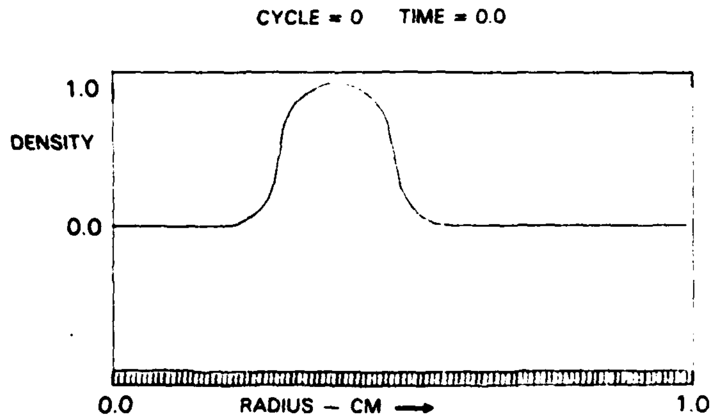
Figure 1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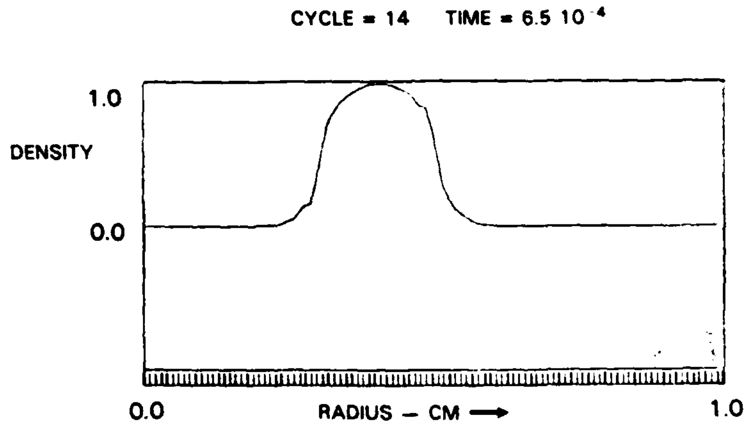
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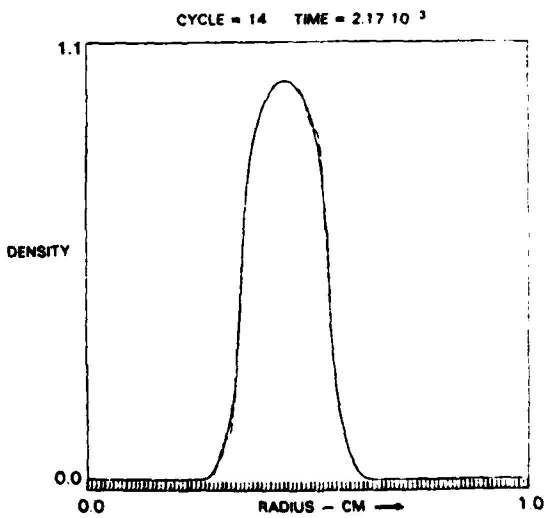
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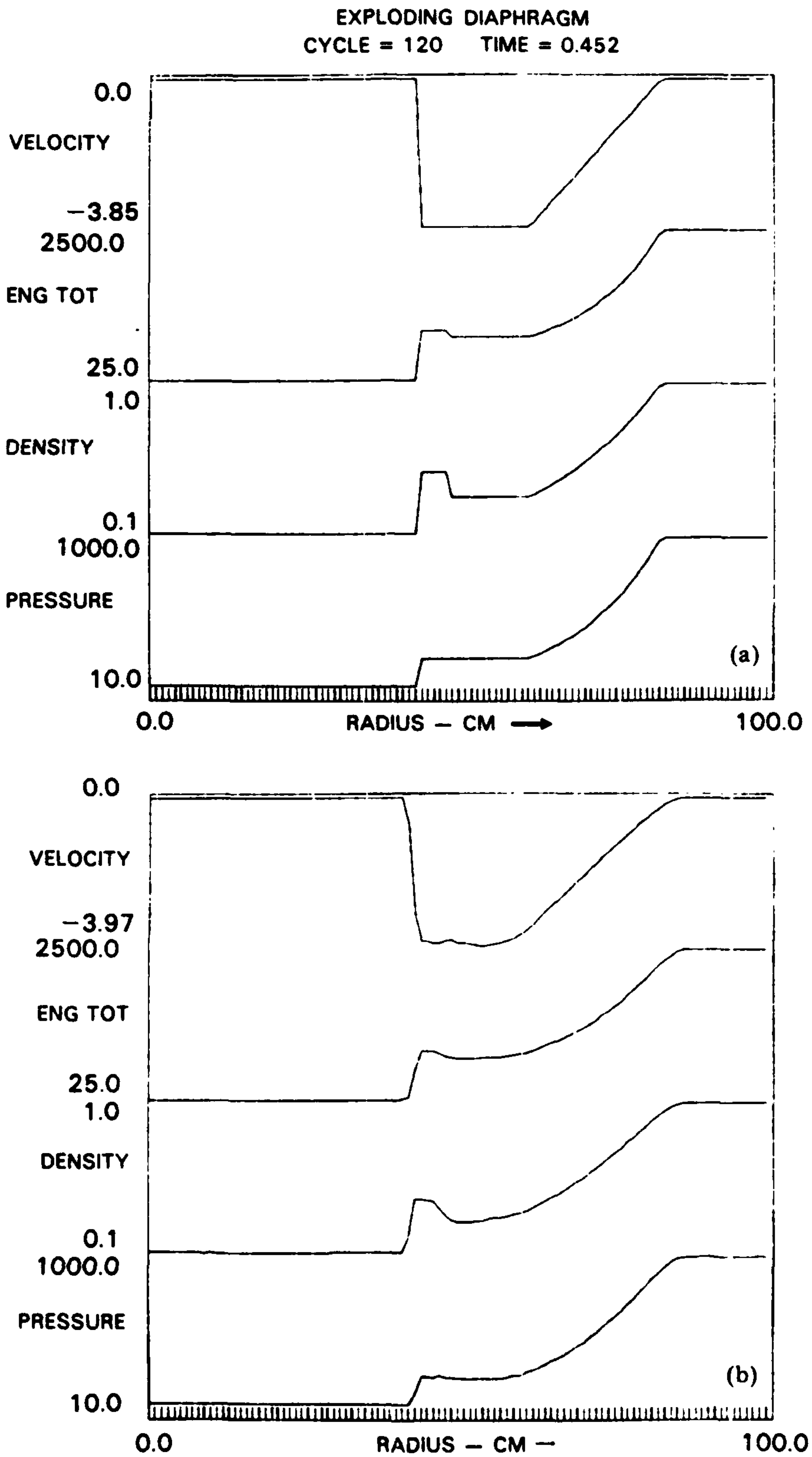
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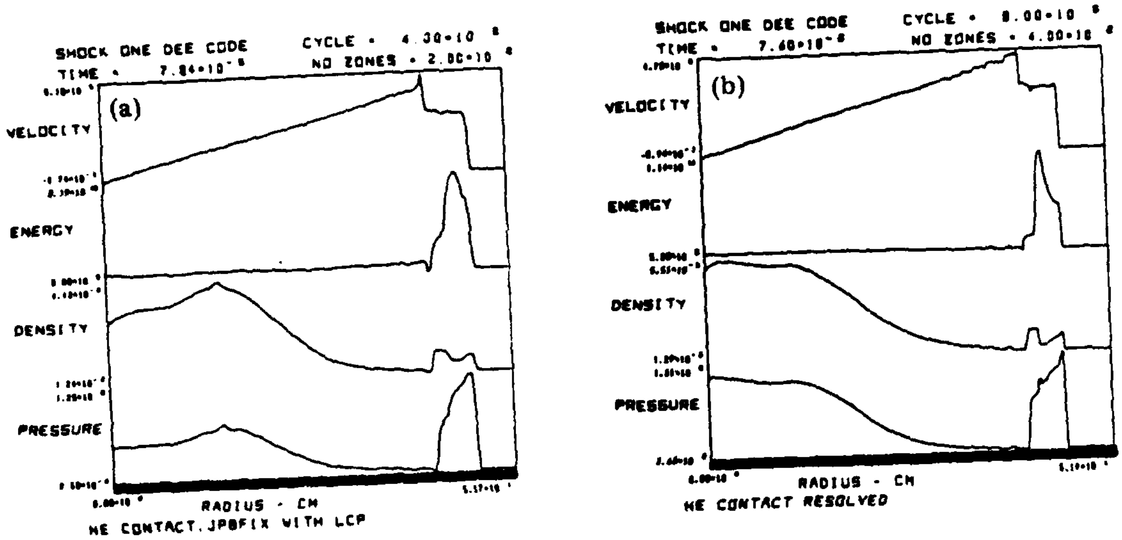
(a)
0.0
RADIUS — CM
100.0
0.0
VELOCITY
−3.97
2500.0
ENG TOT
25.0
1.0
DENSITY
0.1
1000.0
PRESSURE
10.0
(b)
0.0
RADIUS — CM
100.0

Figure 3



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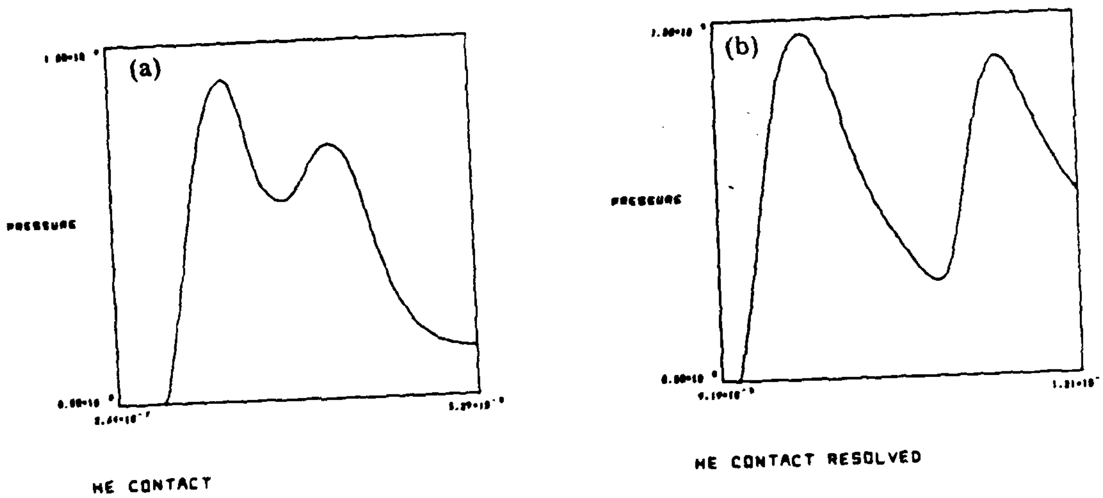


Figure 5

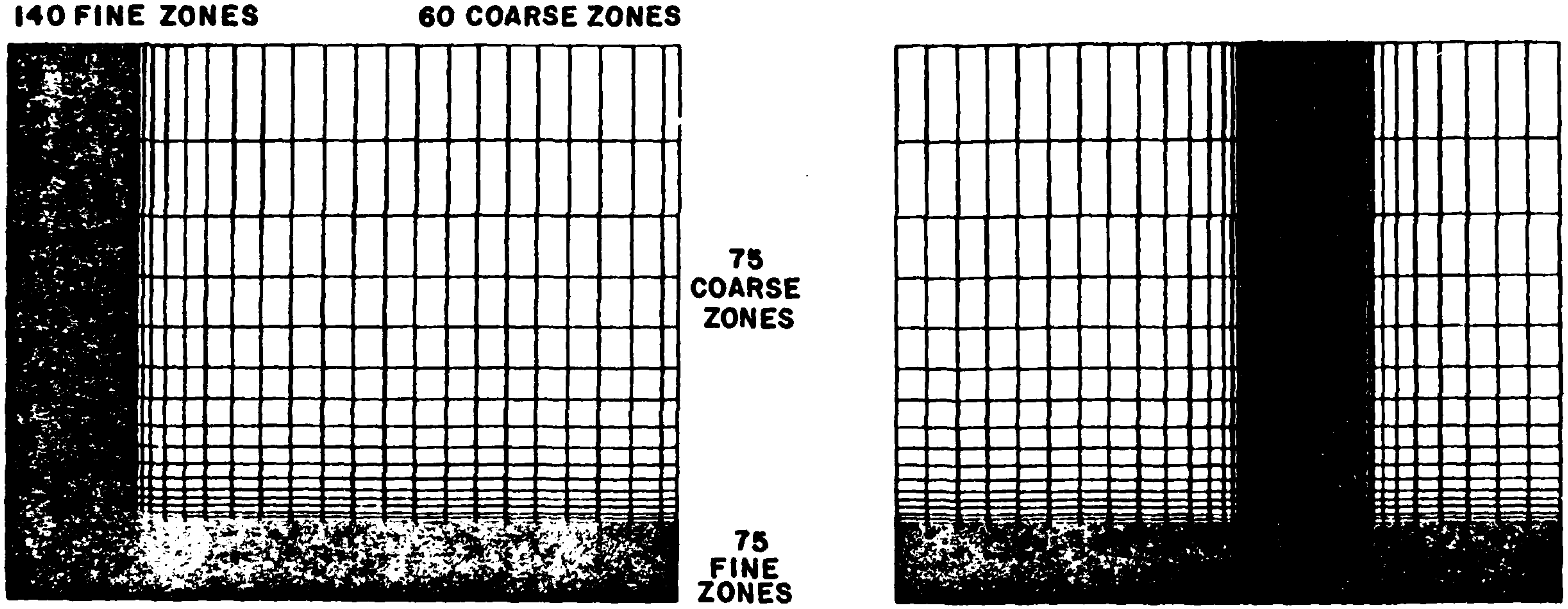
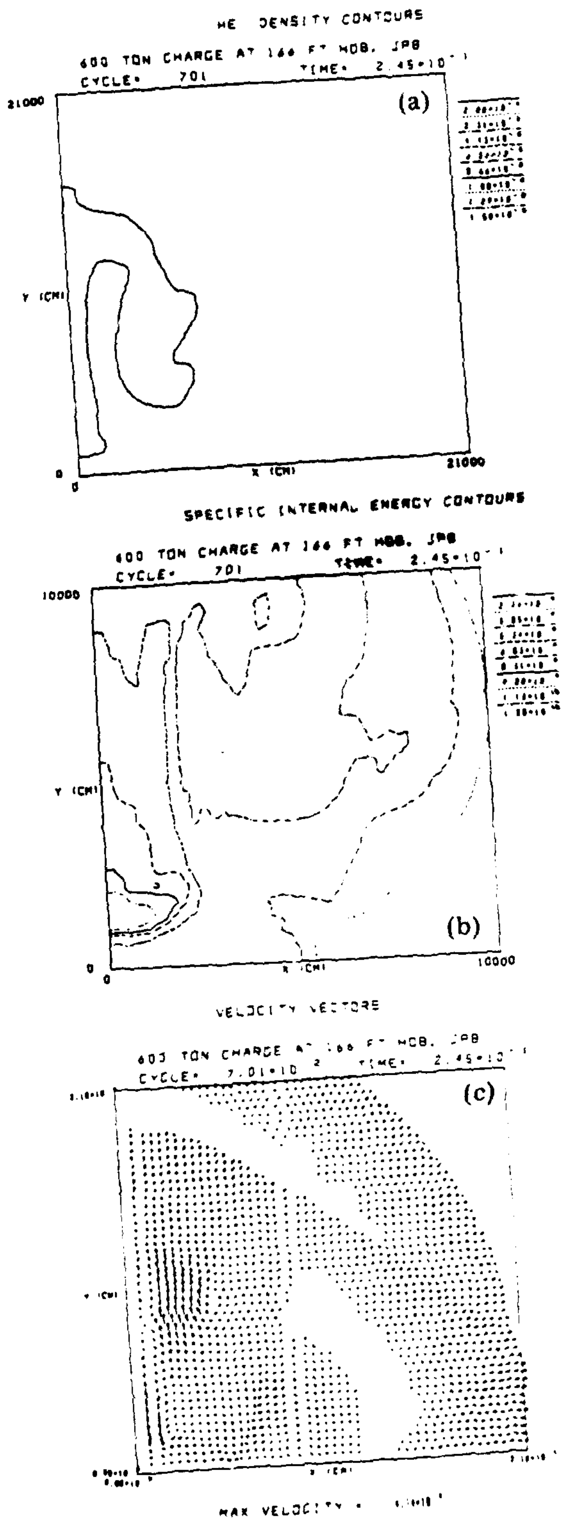


Figure 6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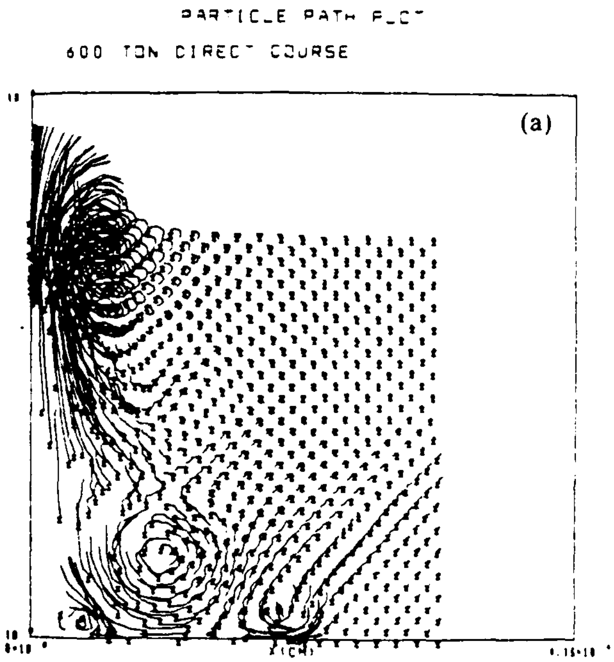
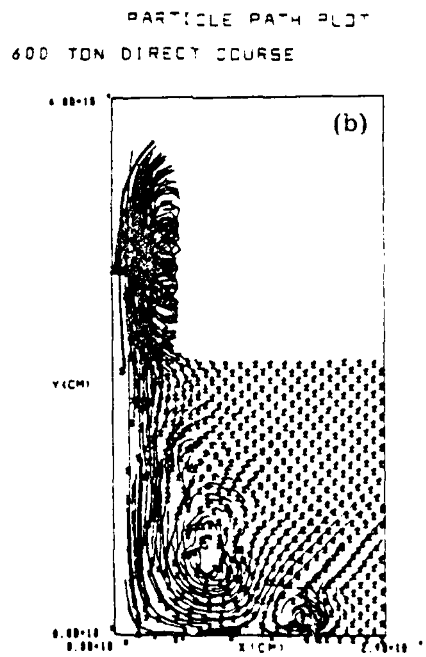
600 TON CHARGE AT 164 FT HOB, JPB
CYCLE= 701
(a)
Y (CM)
X (CM)
21000
SPECIFIC INTERNAL ENERGY CONTOURS
600 TON CHARGE AT 164 FT HOB, JPB
CYCLE= 701
(b)
Y (CM)
X (CM)
10000
VELOCITY VECTORS
600 TON CHARGE AT 164 FT HOB, JPB
(c)
MAX VELOCITY =

Figure 7



Time Interval
1.8 sec. - 3.97 sec.



Time Interval
3.97 sec. - 7.3 sec.

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